

Physical and Optical Structures in the Upper Ocean of the East (Japan) Sea

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LONG-TERM GOALS

This study fits within our broader scientific efforts to understand:

- Physical and biological responses of the upper ocean to atmospheric forcing and how these penetrate to the interior.
- The dynamics and biological influences of instabilities, secondary circulations and vertical motions associated with upper ocean fronts.
- Physical and bio-optical transitions between coastal and central basin waters.

OBJECTIVES

We seek to understand the processes that control physical and bio-optical variability in the upper ocean of the East/Japan Sea. Specifically, we are interested in:

- The upper ocean response to strong wintertime forcing (Siberian cold air outbreaks) at the subpolar front.
- The resulting formation, subduction, and spreading of intermediate waters.

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- The dynamics of the subpolar front.
- Contrasting seasonal and coastal/central basin bio-optical variability.

APPROACH

Two cruises, the first in May 1999 followed by a second in January 2000, sampled upper ocean and atmospheric boundary layer (Drs. C. Dorman, SIO, R. Beardsley and J. Edson, WHOI) variability in the Japan/East Sea. The spring cruise focused on frontal dynamics, characterizing bio-optical variability associated with the spring phytoplankton bloom and documenting the location, range and properties of water masses formed at the subpolar front during the preceding winter. The wintertime cruise documented the upper ocean response to a series of cold air outbreaks with particular attention to processes associated with water mass formation and subduction at the subpolar front. Both cruises employed a towed, undulating profiler (SeaSoar) to make highly-resolved observations of the upper ocean. We used real-time remotely sensed sea surface temperature and ocean color images (R. Arnone and R. Gould, NRL) to determine the location of the subpolar front and to select intensive survey locations. Real-time access to remotely sensed imagery allowed us to modify our sampling in response to changes in the front. Repeated intensive grid surveys provided approximately synoptic, three-dimensional coverage while a sequence of longer sections documented oceanic and atmospheric boundary layer variability away from the front. In addition to the suite of physical and bio-optical sensors carried by SeaSoar, we employed a shipboard Acoustic Doppler Current Profiler (ADCP) and GPS navigation to measure upper ocean currents. Sampling included a limited number of hydrographic stations and optical profiles off the Korean coast and across the subpolar front. Professor S. Yang (Kwangju University) was responsible for additional biological and bio-optical sampling (e.g. nutrient analysis, pigments). Dr. M. Suk (KORDI) and colleagues provided additional support.

WORK COMPLETED

Reports available at the web site listed above document the operational and data processing aspects of both spring and winter cruises. Both efforts involved scientists from the United States, Korea and Russia and included specialists in physical oceanography, biological oceanography, bio-optics, boundary layer meteorology and remote sensing. Motivated by the presence of a clearly defined, strong front, both spring and summer cruises sampled nearly identical regions situated over the northern side of the Yamato Rise. SeaSoar sampling included intensive, quasi-synoptic surveys spanning a region roughly 100 km by 100 km. During winter, several sections extended farther north to encompass a warm eddy sitting just north of the subpolar front and to investigate marine atmospheric boundary layer structure as a function of distance from the source of the Siberian cold air outbreaks. Shipboard sensors made continuous measurements of meteorological variability while atmospheric soundings were carried out each day to obtain vertical profiles of temperature, humidity, pressure and winds. Underway measurements of absorption, scattering, attenuation and remote sensing reflectance were also collected (Dr. R. Arnone NRL).

Physical (Lee and Brink) and bio-optical measurements (Jones), including the shipboard ADCP (Lee and Brink) and meteorological (Beardsley and Dorman) data, have been fully processed and are being employed for scientific analysis. Initial efforts investigated intra-thermocline eddies found south of the subpolar front and employed SeaSoar observations to assist with an evaluation of the Navy's

MODAS operational climatology and nowcast/forecast system. Papers detailing both of these efforts have been published. The collaborative intra-thermocline eddy study characterizes the large pycnostads found in selected locations south of the subpolar front and presents evidence suggesting that subduction at steep meanders may be responsible for their generation [Gordon *et al.*, 2001]. Theoretical and numerical studies conducted by Leif Thomas, a University of Washington graduate student, suggest that Ekman frontogenesis and symmetric instability may be responsible for the formation of strong fronts and for accelerated vertical transports during intense wintertime forcing. Thomas is preparing his results for publication in his doctoral thesis and in the *Journal of Physical Oceanography*. Evaluations of Japan/East Sea MODAS performance using remote sensing and SeaSoar measurements revealed weaknesses in the model's ability to extrapolate accurate vertical structure from surface measurements and illustrated potential pitfalls resulting from mismatches between observed short temporal/spatial scales relative to the longer scales measured by remote sensing [Fox *et al.*, 2001]. Collaborations have also been established between the SeaSoar investigators and ONR-funded Japan/East Sea numerical modelers (e.g. Moores, Hogan and Preller). These efforts focus on employing SeaSoar measurements in model evaluations and on using the numerical simulations to test our observationally-based results.

RESULTS

Strong wintertime forcing by outbreaks of cold, dry Siberian air may drive intermediate water formation and subduction at the subpolar front of the Japan/East Sea. The subpolar front separates warm, saline southern waters from seasonally stratified, colder, fresher waters that lie to the north. In January 2000, four repeat surveys sampled subpolar front evolution through three cold air outbreaks. High-resolution across-front sections reveal $O(10 \text{ km})$ scale lenses embedded in the pycnocline just south of the frontal interface (Figure 1a). These features exhibit anti-cyclonic circulation and have salinities, chlorophyll fluorescence and 2-D potential vorticities similar to those found in the mixed layers north of the front. Significantly, the tilting term $\nabla u / \nabla z \times \nabla s_g / \nabla y$ often causes potential vorticity to be negative at the frontal interface, producing symmetric instability and facilitating rapid vertical exchange of fluid. Comparisons of isopycnal and zonal absolute momentum ($M = u_g - fy$, where u_g is the geostrophic zonal velocity) surfaces highlights symmetrically unstable regions (Figure 1b). When isopycnals slope more steeply than ZAM surfaces, water parcels (tubes) displaced along isopycnals undergo meridional acceleration away from their original location, driving rapid southward transport into the pycnocline. Wintertime cold air outbreaks produce intense negative windstress curl and buoyancy loss over our survey region, both of which act to amplify the tilting term and produce negative potential vorticity. Comparisons of the absolute (planetary + relative) and tilting terms for the regions within 20 km of the front reveal marked contrasts between the two survey periods. In winter, the tilting term produces negative potential vorticity in approximately 8% of the data (Figure 2), while in spring, when atmospheric forcing is weak, the tilting term remains small and none of the sections exhibit negative potential vorticity.

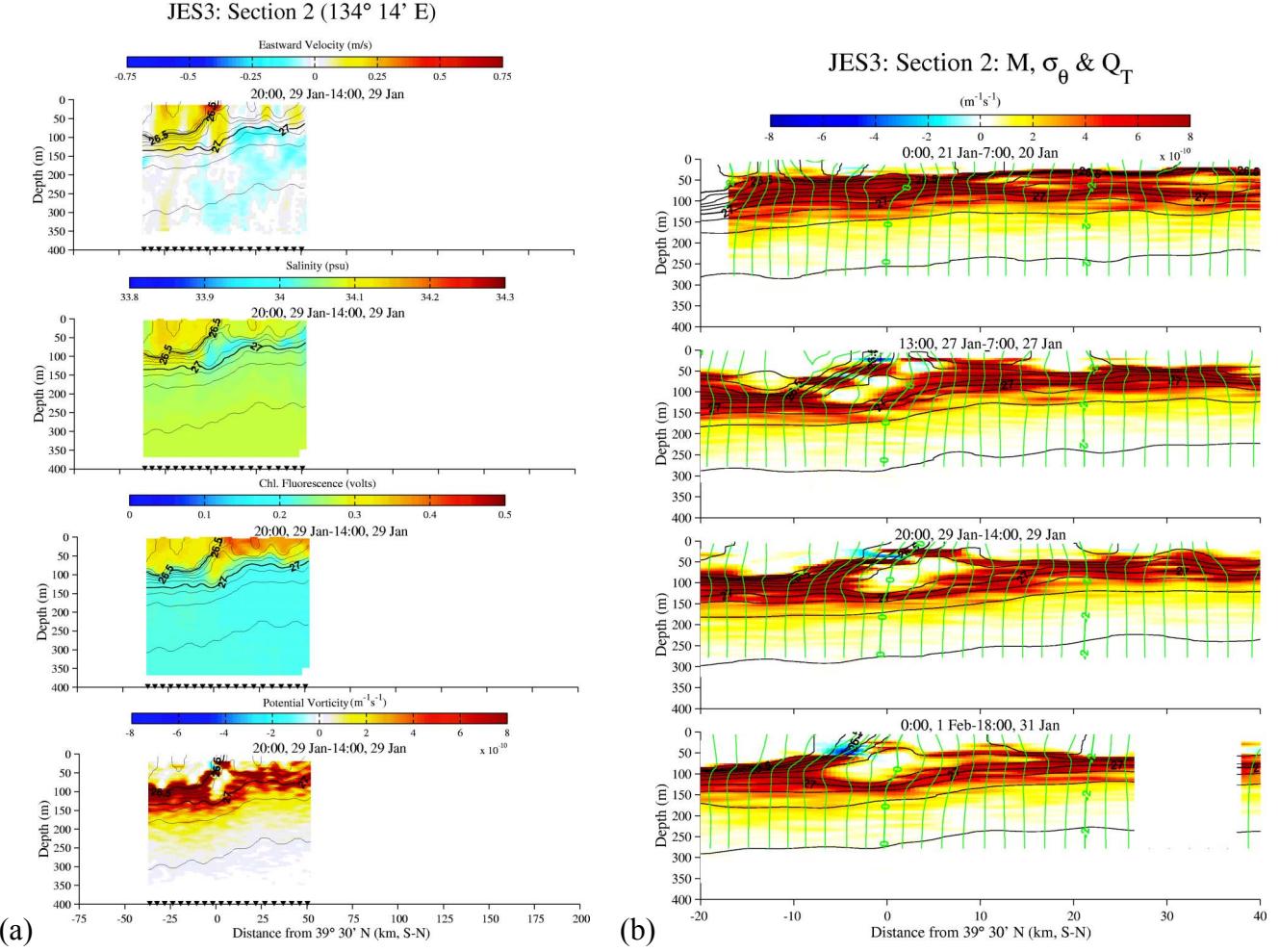


Figure 1. (a) Wintertime cross-front section with eastward velocity, salinity, chlorophyll fluorescence and 2-D potential vorticity colored over \square contours. Triangles mark the locations of SeaSoar profiles. An anticyclonic lens sits between 50-150 m, just south of the front. Waters in the lens are relatively fresh, exhibit elevated chlorophyll fluorescence and low potential vorticity, similar to properties within the north-side mixed layer. **(b)** Zonal absolute momentum surfaces (green) and isopycnals (black) with 2-D potential vorticity for the four repeat occupations of a wintertime section. Note the change in vertical and horizontal scales from (a). Regions with negative potential vorticity, where isopycnals slope more steeply than ZAM surfaces, are symmetrically unstable.

Potential Vorticity at the JES Subpolar Front

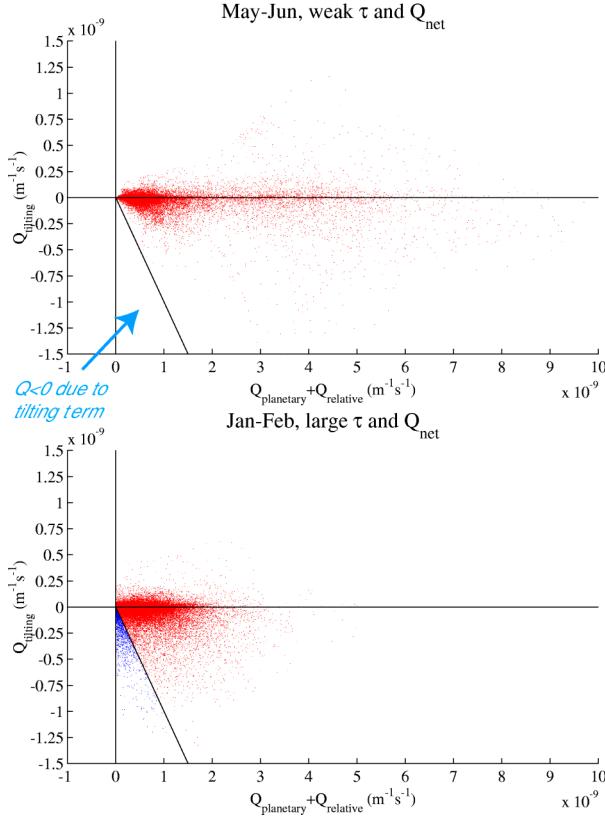


Figure 2. Potential vorticity (absolute and tilting terms) calculated at all points within 20 km of the subpolar front (as defined by density gradient maxima), from all sections occupied in spring 1999 and winter 2000. Atmospheric forcing was weak in springtime and strong (intense winds and surface buoyancy loss) in winter. Blue points mark negative potential vorticity produced by the tilting term. Negative potential vorticity appears only in the wintertime sections.

IMPACT/APPLICATION

Highly resolved, three-dimensional upper ocean measurements provide a unique picture of the integrated effects of wintertime water mass formation in response to strong atmospheric forcing. Simultaneous measurements of bio-optical properties contrast conditions on either side of the front and permit us to study the role of dynamics in controlling bio-optical variability. Both at the subpolar front and off the Korean coast, SeaSoar surveys provide bio-optical measurements of unprecedented synopticity and horizontal resolution.

TRANSITIONS

None.

RELATED PROJECTS

Our efforts are part of an intensive, multi-investigator study of the Japan/East Sea. We anticipate cooperation with the following components:

Satellite Characterization of Bio-Optical and Thermal Variability in the Japan/East Sea, B. Arnone, (NRL).

Atmospheric Forcing and its Spatial Variability over the Japan/East Sea, R. Beardsley, A. Rogerson (WHOI) and C. Dorman (SIO).

Optical Properties as Tracers of Water Mass Structure and Circulation, G. Mitchell, D. Stramski and P. Flatau (SIO).

Modeling Support for CREAMS II: Oceanic and Atmospheric Mesoscale Circulation and Marine Ecosystem Simulations for the Japan/East Sea, C. Mooers and S. Chen (University of Miami).

Wind Forcing of Currents in the Japan/East Sea, P. Niiler (S.I.O.), D. Lee (Pusan National University) and S. Hahn (National Fisheries Research and Development Institute).

Observations of Upper Ocean Hydrography and Currents in the Japan/East Sea using PALACE Floats, S. Riser (University of Washington).

Hydrographic Measurements in Support of Japan/East Sea Circulation, L. Talley (SIO).

Shallow and Deep Current Variability in the Southwestern Japan/East Sea, R. Watts and M. Wimbush (University of Rhode Island).

PUBLICATIONS

Fox, D.N., W.J. Teague, C.N. Baron, M.R. Carnes, and C.M. Lee, 2002: The Modular Ocean Data Assimilation System (MODAS), *Journal of Atmospheric and Oceanic Technology*, 19, 240-252.

Gordon, A.L., C.F. Giulivi, C.M. Lee, A. Bower, H.H. Furey, and L. Talley, 2002: Japan/East Sea Intra-thermocline Eddies, *Journal of Physical Oceanography*, 32, 1960-1974.

Lee, C. M., C. E. Dorman, R. W. Gould and B. H. Jones (1999) Preliminary Cruise Report: Hahnaro 5-Dynamics, Biology, Optics and Meteorology of the Subpolar Front in the Japan/East Sea. Technical Memorandum, APL-UW TM 3-99, Applied Physics Laboratory, University of Washington, 65pp.